WHANGPOO
CONSERVANCY BOARD

S. H. I. Series I, No. 2

Hydrological Data

for the

Yangtse Estuary

Obtained

up to 1918

WHANGPOO CONSERVANCY BOARD

SHANGHAI HARBOUR INVESTIGATION

(SERIES I. GENERAL DATA;—No. 2)

HYDROLOGICAL DATA

FOR THE

YANGTSE ESTUARY

OBTAINED

PREVIOUS TO 1918

SHANGHAI, 1919

Printed by the COMMERCIAL PRESS, Limited
SHANGHAI
1919

PREFATORY NOTE

The hydrological data published in the previous "Report on the Yangtse Estuary" of April, 1917, have since been supplemented by the Hydrometric Department, more especially by continuous tide readings and silt-sampling at the Kiangyin and Side Saddle Stations, and further analyzed, and an attempt is here made to provide a synopsis of the limited data available conveniently formulated for river and harbour engineering purposes.

To this end certain generalizations have had to be made and in some cases even assumptions have been required to supplement facts, as the information is very scanty on many points. The observations on which this synopsis is based only cover short and/or intermittent periods during the Board's Estuary investigation in 1915–1916–1917, as recorded in the above report, with the exception of the following permanent tide and water observation stations:—

Woosung:	*from 1912 to date (Customs readings from 1880–1912).*
Kiangyin:	*from 1915 to date.*
Side Saddle:	*from 1915 to date.*

Only further observations on a large scale can, however, remedy deficiencies. For the time being, it has therefore been thought worth while to solidify the material collected and analyzed and when in doubt to state the deficiency but also the probable conclusions, reserving their confirmation for future occasion.

This synopsis will thus show what we know and also what we do not know about the tides and hydrography of the Estuary, which latter is equally important for future observation.

The control of the tide readings at Side Saddle has only been possible by the kind assistance and coöperation of the Coast Inspector of the Maritime Customs, who has allowed us the benefit of the use of the Customs revenue steamer regularly visiting the Islands.

The preparation of these statistics, diagrams, etc., has been done by the Board's Hydrometric Department. Dr. H. Chatley has ably supervised the work and assisted in preparing and editing this report.

Shanghai, May, 1919.

H. von HEIDENSTAM,

Engineer-in-Chief.

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YANGTSE ESTUARY

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(A) THE TIDAL WAVE AND ITS PROPAGATION

Origin and Direction.

The main or forced tidal wave circulates from East to West in the Antarctic ocean and a secondary free wave proceeds toward China in a Southeast to Northwest direction. In the China Sea the cotidal lines, i.e., lines connecting points where high water occurs at the same time at full and change of the moon, indicate a general progression in the same direction, veering north as the mouth of the Gulf of Chihli is approached (see Plate No. 4 in Report No. 2 on the Hydrography of the Whangpoo). The speed decreases with the depth. The wave enters the various mouths of the Yangtse almost simultaneously (see Plate No. 35 in the Report No. 1 on the Yangtse Estuary).

Time.

At any given locality high water occurs at a fairly constant interval after the moon crosses the meridian which is termed the "mean establishment." A table of the values of this interval for various places on the Yangtse is given in Report No. 1 (page 32) and shows that the interval changes from 10h. 09m. at Side Saddle to 12h. 22m. (2 minutes before the transit) at Woosung, 5h. 0m. at Kiangyin, and 14h. 24m. at Wuhu. At new and full moon the interval is 25 minutes longer than the mean (see Plate No. 1).

Magnitude.

The "reference tide" employed throughout the observations is the Woosung tide, being the one most fully observed (see preface) and is for the Whangpoo the master tide. Full particulars of this are given in the Report No. 2 on the Hydrography of the Whangpoo.

From this it appears that the mean tidal range is 7.30 feet, mean high-water level 10.20 feet, mean low-water level 2.90 feet, above Woosung Horizontal Zero, from long averages.

The mean spring range is about 10 feet and the mean neap range about 4 feet.

Owing to the changes in the declination of the sun and moon, there is a mean diurnal inequality in height between successive high waters of ± 1.7 feet and between successive low waters of ± 0.45 feet.

The *mean tidal range* (for all tides) from Side Saddle to Wuhu is shown on Plate No. 2. Irregularities occur near Plover Point owing to the inequalities of phase between the component waves which enter through the two branches.

The relative ranges at different lunar epochs are in the average closely related to the moon's hour angle. Plate No. 3 shows the mean values of the range at Woosung and Side Saddle for the various days of the moon. (A gross diurnal inequality of 2.5 feet between alternate pairs of ranges may

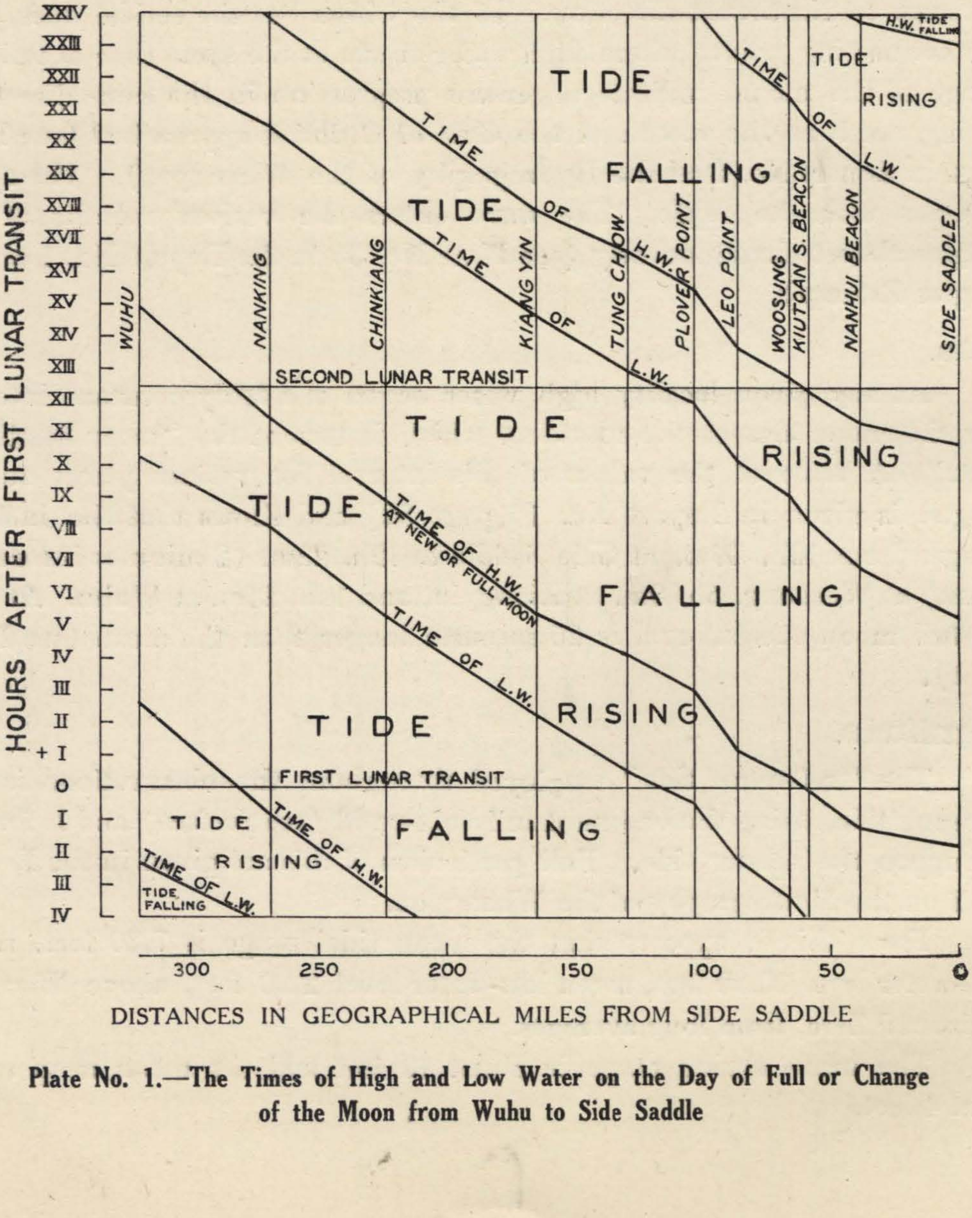

Plate No. 1.—The Times of High and Low Water on the Day of Full or Change of the Moon from Wuhu to Side Saddle

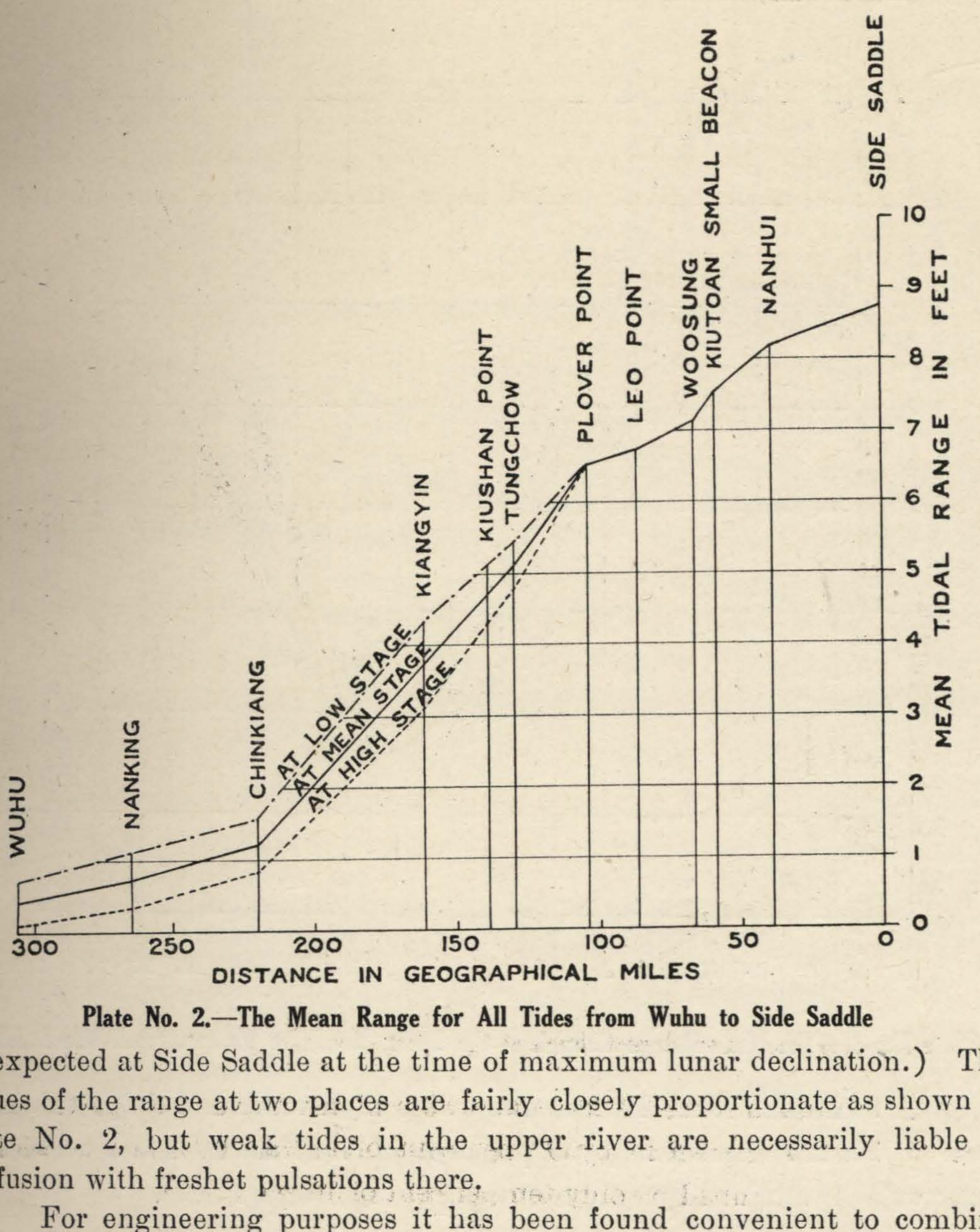

Plate No. 2.—The Mean Range for All Tides from Wuhu to Side Saddle

be expected at Side Saddle at the time of maximum lunar declination.) The values of the range at two places are fairly closely proportionate as shown in Plate No. 2, but weak tides in the upper river are necessarily liable to confusion with freshet pulsations there.

For engineering purposes it has been found convenient to combine statistically the observations on the duration or frequency principle and so standardize the tides in the Yangtse as follows:—

A Standard Spring Tide is one whose high-water and range values are those which are exceeded by only ten per cent* of all actual tides and whose low-water value is exceeded by 90 per cent of all actual tides.

*Ten per cent in the average obviously covers 1½ days (i.e., three tides) out of the fortnightly period, so that the underlying assumption is that the three successive tides at the correct lunar epoch are springs. Elsewhere (see Y. R. No. 1) four successive tides have been employed.

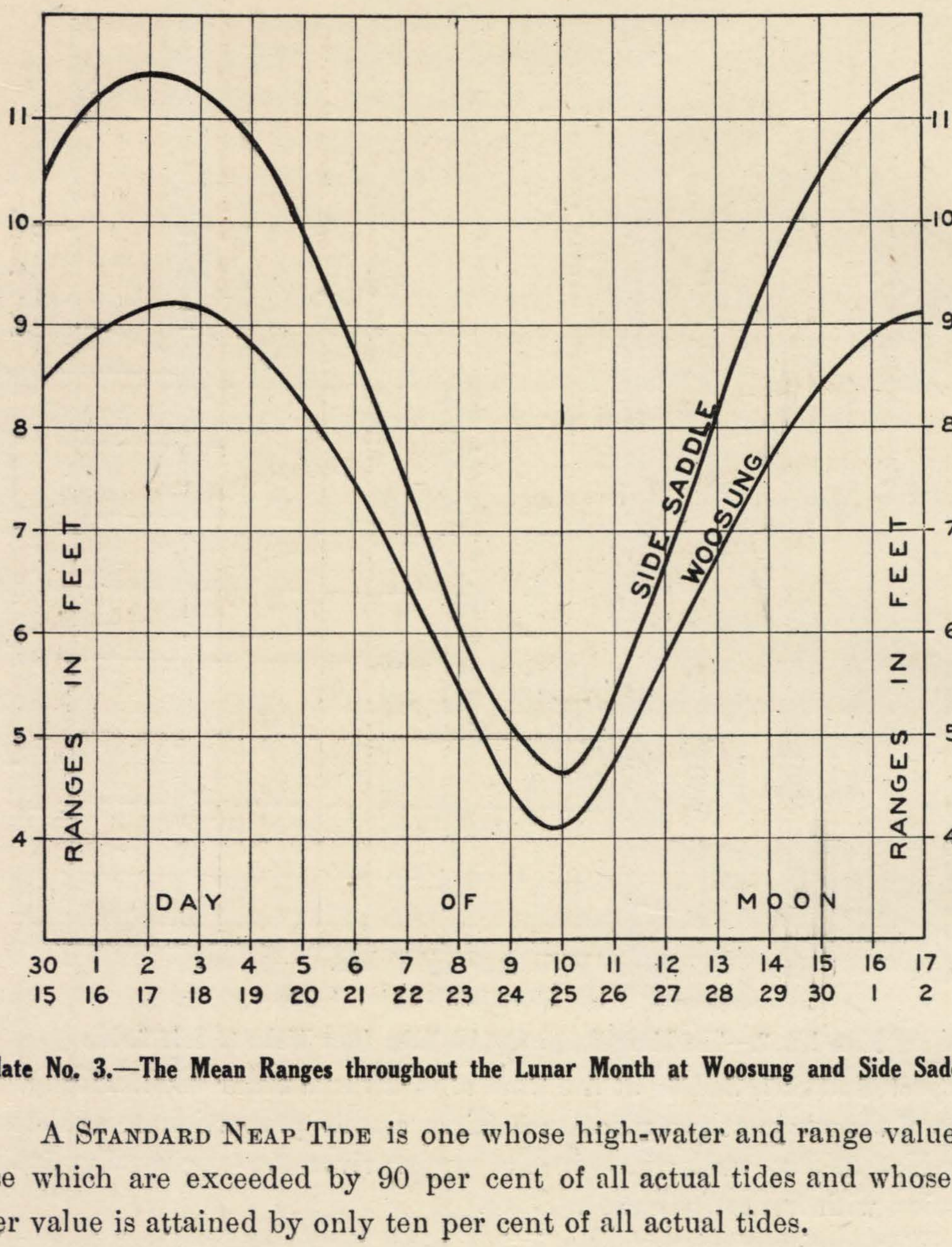

Plate No. 3.—The Mean Ranges throughout the Lunar Month at Woosung and Side Saddle

A STANDARD NEAP TIDE is one whose high-water and range values are those which are exceeded by 90 per cent of all actual tides and whose low-water value is attained by only ten per cent of all actual tides.

When referred to a constant level datum these definitions are not consistent for reaches with a large variation of "stage" owing to run-off but they are quite suitable for the lower part of an estuary.

The standard values for the entire Estuary from Side Saddle to Kiangyin are shown in Plate No. 4. The values at the Bar have been obtained by the comparison of short period observations with interpolations made from the Side Saddle and Woosung continuous records.

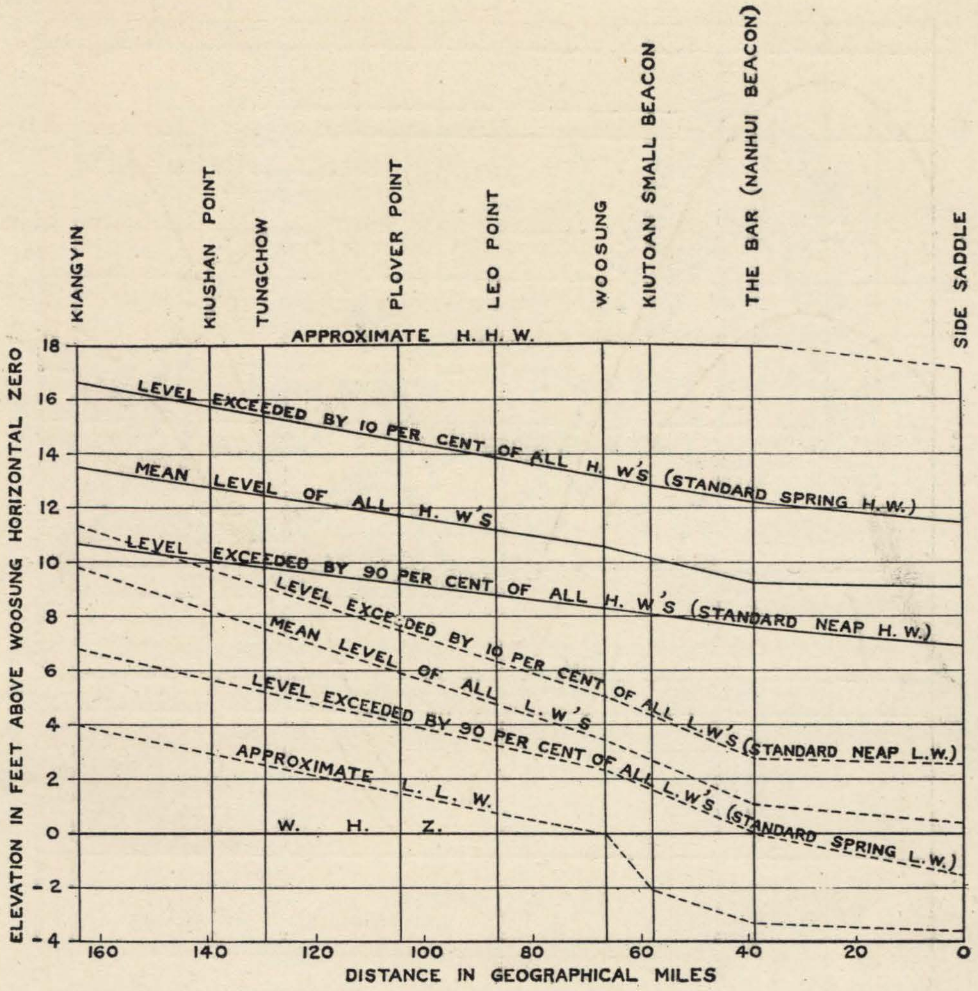

Plate No. 4.—Standard Tidal Levels from Kiangyin to Side Saddle

The mean tide at the Bar in the South Channel appears to have a *range* of 8.2 feet, the standard spring range being 12.3 feet and the standard neap 4.8 feet, but there is apparently a tendency at times to heap up on the Bar (see Table No. 6, page 34, Yangtse Estuary Report No. 1, which gives ranges ten per cent greater on the Bar than at Side Saddle during June, 1916).

Depths and Levels at the Bar (Fairy Flats).

The table (No. 1) shows the approximate levels and depths a the Fairy Flats. Plate No. 5 indicates the manner in which the depths change during a lunar day.

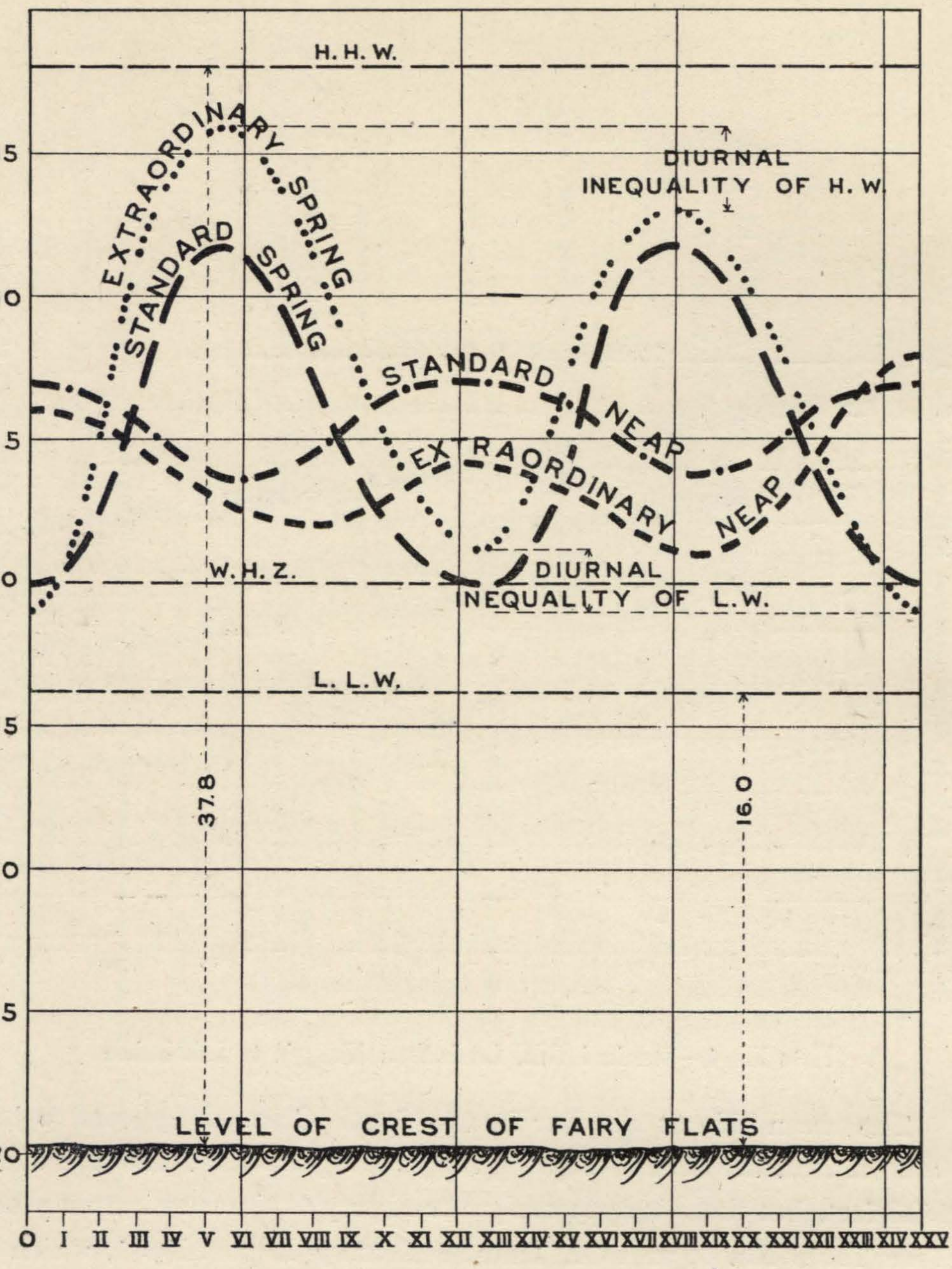

Plate No. 5.—Typical Tides and Depths at the Fairy Flats (Yangtse Bar)

Levels and the "Stage" of the River.

The "half tide" level (or mean level) of any one wave may differ considerably from the annual mean level, since the propagation is affected by wind and by the stage of the river due to the annual inequality of run-off. Plate No. 6 shows the mean range of the annual oscillation of level due to

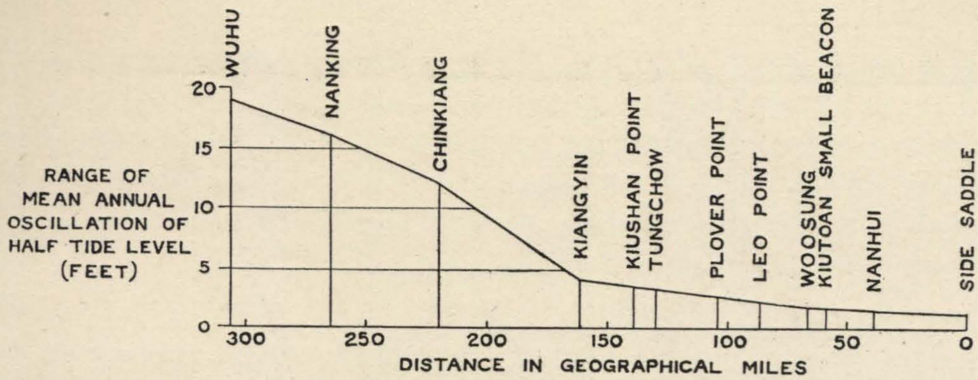

Plate No. 6.—The Mean Annual Oscillation or "Change of Stage" from Wuhu to Side Saddle

run-off (see also Table No 9, page 43, in the Yangtse Estuary Report No. 1).

The actual rise and fall of the half tide level during any one year may vary considerably (say as much as ± 40%) from these mean values. The stage does not cause any appreciable variation in the tidal range in the Estuary (it does however affect the levels to the extent of a few feet below the Langshan Flats), but at Kiangyin the high stage tides are about 33 per cent smaller in range than at low stage (see Plates 46 and 47, Yangtse Estuary Report No. 1, pages 41 and 42). At Wuhu the tidal range is almost zero at time of high water but may amount to two feet or more at low river.

Table No. 1

STANDARD WATER LEVEL AT FAIRY FLATS

(Nanhui Beacon)

	Level reduced to W. H. Z.	*Rise*	*Depth on Crest*	*Seasonal Correction to be applied for January*	*July*
Highest High Water	18.0	21.8	37.8		
Standard Spring High Water ...	11.8	15.6	31.6	–0.33	+1.35
Mean High Water	9.6	13.4	29.4	–0.62	+1.24
Highest Low Water	8.6	12.4	28.4		
Standard Neap High Water... ...	7.0	10.8	26.8	–0.10	+1.27
Mean Water Level	5.4	9.2	25.2		
Standard Neap Low Water	3.6	7.4	23.4	–1.22	+0.39
Mean Low Water	0.8	4.6	20.6	–0.30	+0.81
Lowest High Water	0.2	4.0	20.0		
Standard Spring Low Water ...	–0.0	3.8	19.0	–0.28	+0.28
Lowest Low Water	–3.8	0.0	16.0		

Propagation.

From a consideration of the time of high water and low water at the various places, the speed of propagation of the wave has been computed

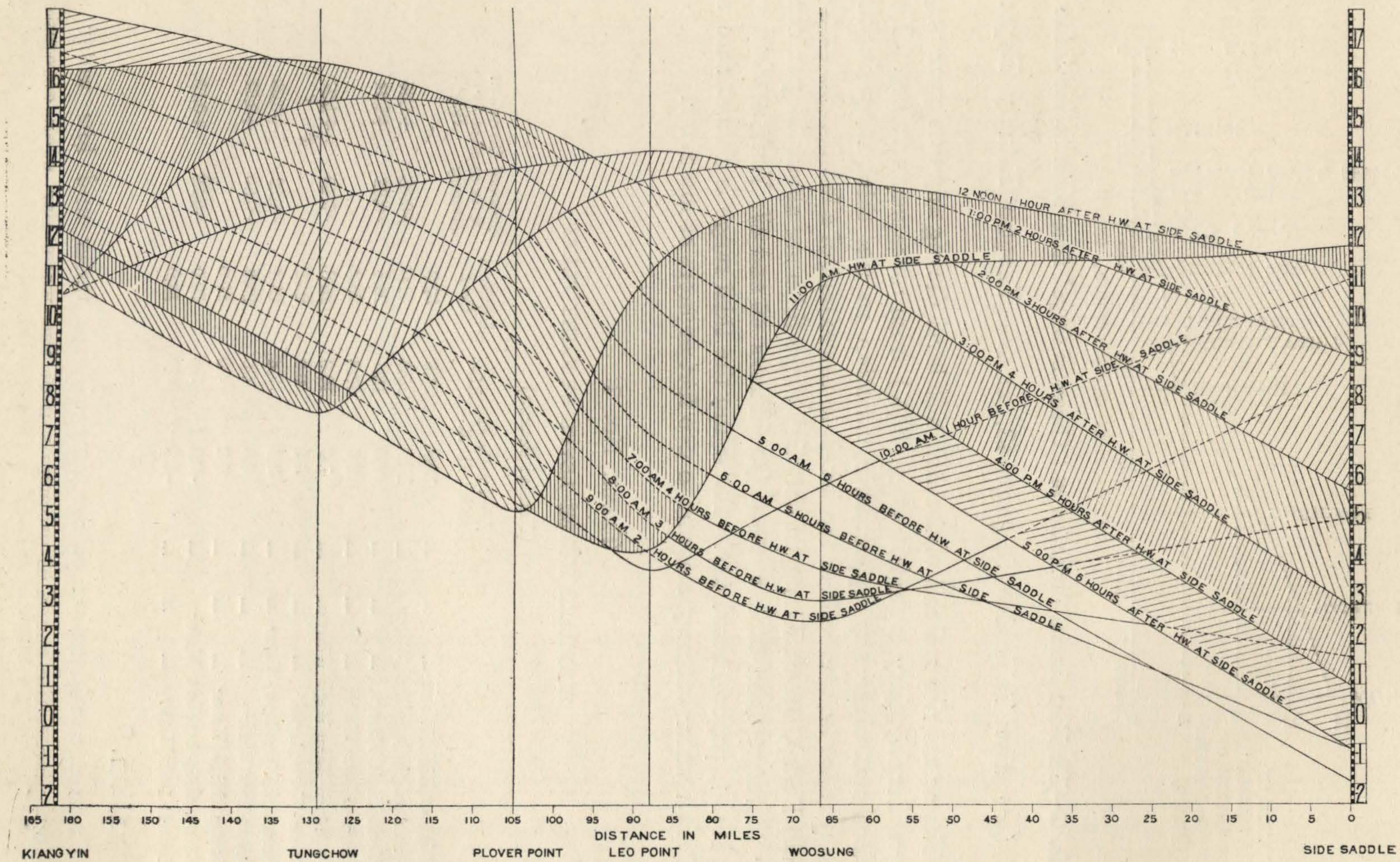

Plate No. 7.—Profiles of Water Surface at One Hour Intervals, Kiangyin to Side Saddle, Spring Tide

and is given in Yangtse Estuary Report No. 1, Tables 5, 6*, 7, and 8 (pages 33, 34, and 35). It appears that the mean speed from Side Saddle to Wuhu is 18½ knots for the head of the wave and 16 for the foot, but in the open water between Side Saddle and Nanhui speeds of 57 knots for the head and 30 knots for the foot have been observed. The depths computed from the speeds by the standard formula agree only moderately well with the actual depths.

Proceeding up the Yangtse the range steadily decreases until at Ta Tung, 50 miles above Wuhu, it becomes imperceptible. In the summer the limit is at Wuhu and it has not been considered necessary to consider any tidal action above that place. The form of a typical tidal wave as far as Kiangyin is shown on Plate 7 and there are also numerous examples given in Report No. 1 on the Yangtse Estuary (Plates Nos. 20–34).

The rise becomes more abrupt as the river is ascended as far as Kiangyin.

Duration of the Rise and Fall.

At Side Saddle the periods of rise and fall are practically equal, averaging 6h. 12m. each. At Woosung the mean time of rise is 4h. 44m. (diminishing to 3h. 50m. at springs and increasing to 5h. 38m. at neaps).

The most rapid rise occurs at Kiangyin (mean value 4h. 12m.) and may probably be associated with the extinction of the flood current which occurs there.

The duration of various levels over the bar is shown in Plate 8. These levels are reduced to Woosung Horizontal Zero and to find the corresponding depths 19¾ feet must be added.

Accuracy of Forecasts.

Predictions of the tidal levels at Woosung have been made by the U. S. Geodetic and Coast Survey and also specially for the Whangpoo Conservancy Board for the year 1918 by the Director of the Nautical Almanac Office (London) and it appears that in the absence of strong wind an accuracy of ± 14 minutes in time of H.W. and ± 0.6 feet in level can be obtained. With strong winds errors of half an hour in time of H.W. and two or three feet in level may occur. L.W. is more irregular than H.W.

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*(Footnote: Table No. 6 contains a clerical error: The distance from Kiutoan Small Beacon to Woosung should be 8.7 nautical miles, the two velocities should be 19.33 and 9.49 knots respectively and the computed depth 30.7 feet).

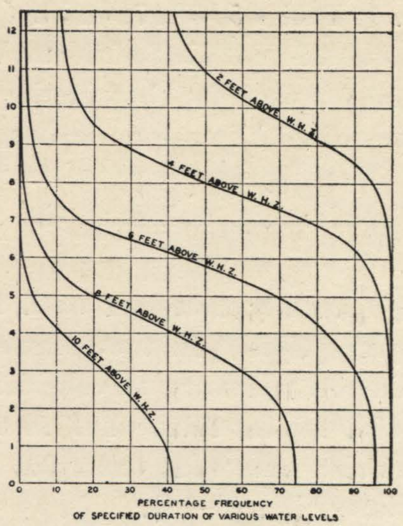


Plate No. 8.—The Frequency of Occurrence of a Specified Duration of a Given Water Level at the Fairy Flats. 19.75 feet must be added to find depths

(*Example of Use:* How often does a level of 8 feet above W. H. Z. [=27.75 depth] endure for 5 hours? *Answer:* 18½% of all tides)

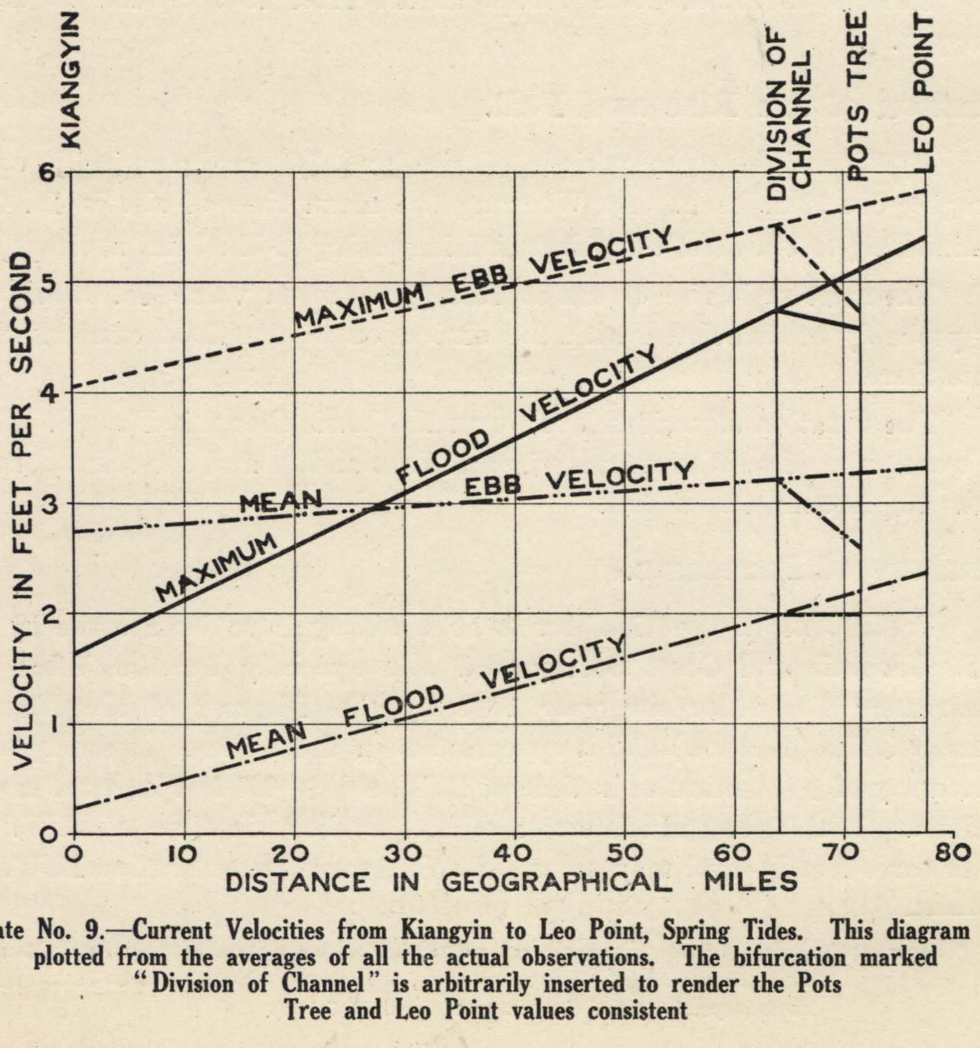


Plate No. 9.—Current Velocities from Kiangyin to Leo Point, Spring Tides. This diagram is plotted from the averages of all the actual observations. The bifurcation marked "Division of Channel" is arbitrarily inserted to render the Pots Tree and Leo Point values consistent

(B) CURRENTS

Origin: Tidal and Fluvial.

There are strong currents in the lower Yangtse which are due partly to the discharge of the run-off and partly to the transmission of the tidal wave. The upstream or flood current is stronger than the ebb in the lower part of the Estuary owing to the rapidity of the rise but it lasts less time. In the upper part of the Estuary the ebb is stronger than the flood.

Magnitudes.

The information as to the values of current velocities in the Yangtse given in the Yangtse Estuary Report No. 1 (pages 36–52) is fairly complete. The following table of calculated means and observed maximum values (in feet per second) taken from our actual observation series is interesting:—

	Observed		Calculated	
	Maximum Filament Values		Maximum value of Mean over whole section during *whole* discharge	
	Flood	*Ebb*	*Flood*	*Ebb*
Pots Tree	5.31	5.28	2.79	3.54
Leo Point...	6.27	6.44	2.86	3.37
Kiangyin	2.70	6.30	1.87	3.92

The graphs show mean values for strong and weak tides as nearly as the observations made permit (Plates 9 and 10).

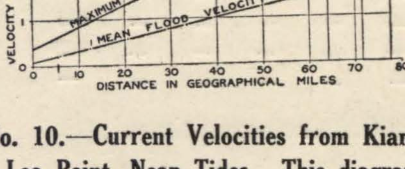


Plate No. 10.—Current Velocities from Kiangyin to Leo Point, Neap Tides. This diagram is similar to Plate No. 9

Distribution of Velocities in Section.

A careful analysis of vertical velocity curves (see Yangtse Report No. 1, pages 43–47) in divisions of the various sections shows that the

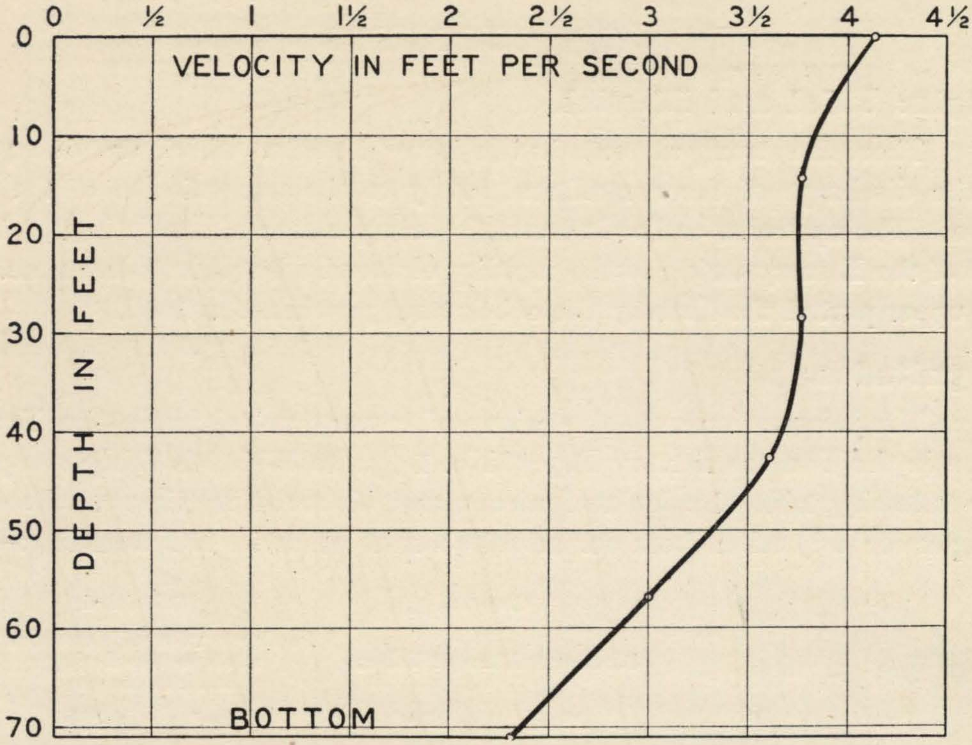


Plate No. 11.—Actual Observed Current Velocities in a Vertical at Leo Point

velocity equivalent to the mean occurs at from 30 to 67 per cent of the depth from the bottom, but is usually about 40 per cent (i.e., 60 per cent from the surface), and that the mean velocity in a division of the section is from 80 to 96 per cent of the actual velocity at 20 per cent of the depth from the surface.

The bottom velocities, which are important in connection with scouring, average as follows in relation to the mean for the whole of a compartment of a section:

	Flood	*Ebb*
Pots Tree	0.7	0.7
Leo Point	0.6	0.7
Kiangyin	0.8	0.65
Wuhu	—	0.80

Values lower than 0.4 are exceptional.

An actually observed vertical velocity curve at Leo Point is shown in Plate 11.

The transverse distribution depends on the curvature and form of the section. In general the maximum velocities occur toward the deepest part of the section.

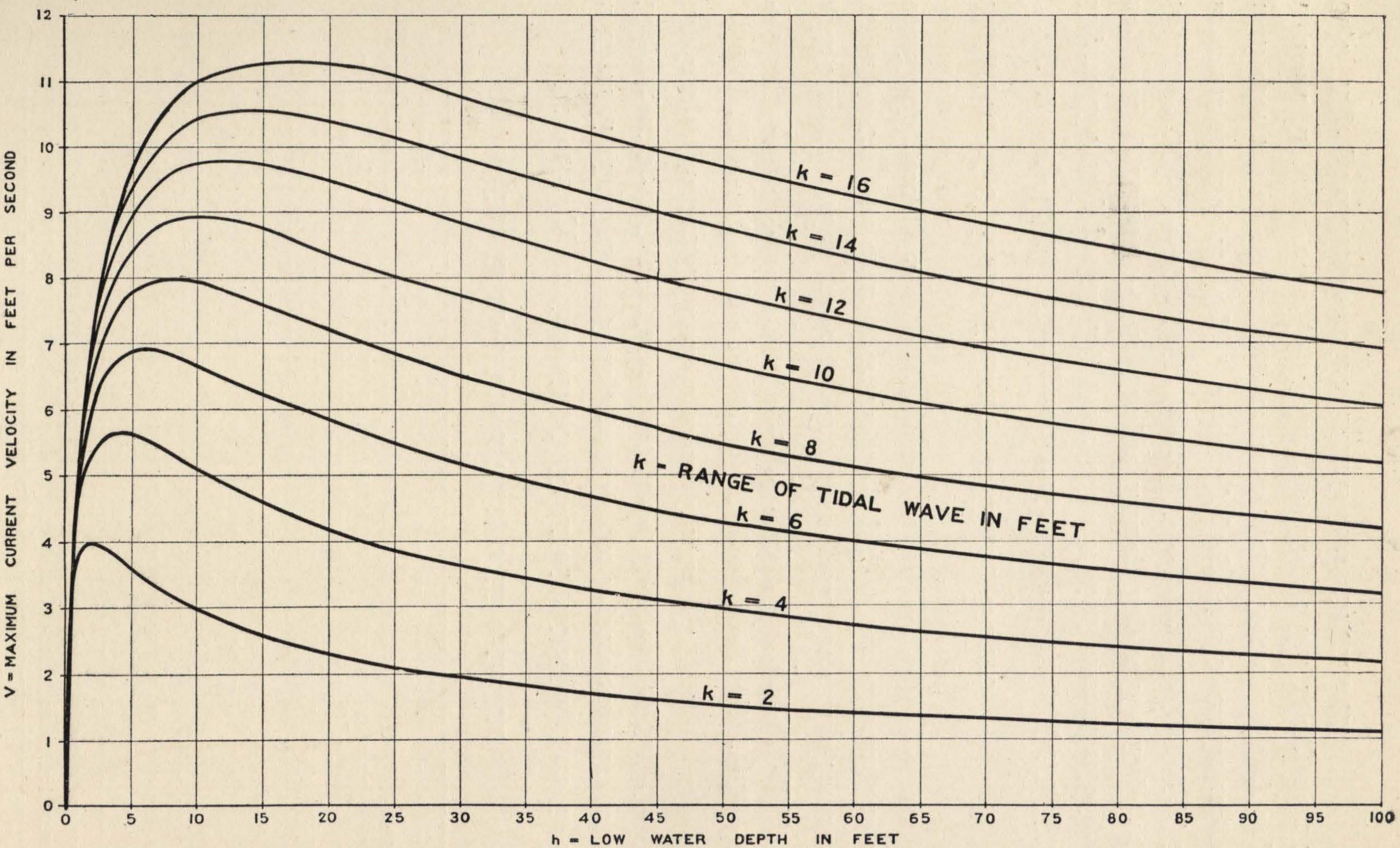


Plate No. 12.—Theoretical Relation between Range of Tide, Depth of Water, and Maximum Current Velocity (See Report No. 2 on the Hydrography of the Whangpoo, Page 80). This relation is only approximate for natural and irregular channels, since the depth is assumed constant and bank effects are neglected

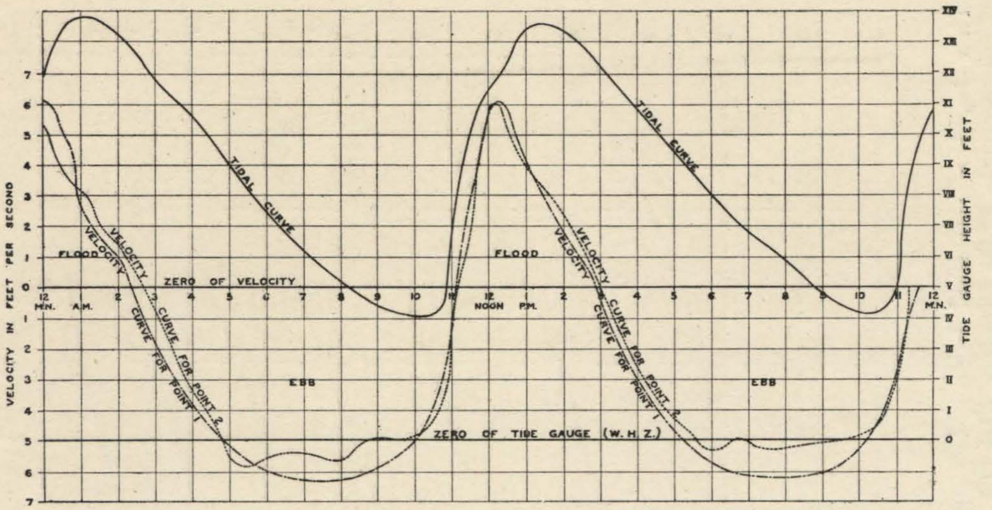


Plate No. 13.—Relation of Velocity to Tide at Leo Point

It would appear that with feeble flood velocities there is a more uniform distribution of velocity, possibly due to more extensive turbulence. The current turns first in the weakest part of the stream so that the distribution is anomalous until the whole stream has turned.

With regard to the lateral distribution, equal velocity curves (see Yangtse Report No. 1, pages 47-52) have been plotted from sets of simultaneous vertical velocity observations and show that the maximum velocities tend to occur over the deep part of the channel but may be considerably eccentric.

Relation of Current Velocity to Tidal Wave.

A study of the Whangpoo records has confirmed (vide Whangpoo Report No. 2, pages 36–38) the relation of tidal current velocity to tide suggested by Plates 40–44 in Yangtse Estuary Report No. 1, pages 37–39, i.e., the total range of velocity (max. ebb + max. flood velocity) in mid-stream at one fifth the depth, is roughly proportionate to the range of the tidal wave and when both these are measured in foot units, they happen to be about the same value (see Whangpoo Report No. 2, appendix 2, page 80). A graph of the theoretic relation is shown in Plate 12.

A new example of this parallelism is given in Plate No. 13 taken at random (24th Sept., 1915) from the current records for Leo Point. The form of the two curves, range and current velocity, may differ somewhat. A continuous record for a whole month in the Whangpoo confirms the general constancy of this relation.

The two phenomena keep step in a fairly regular manner and in many cases it is possible to apply the following empirical rules:—

General Characteristics of Currents in Relation to Tide Level in Any One Cross-section.

(1) The tidal level cycle lags after the current cycle.

(2) Maximum flood velocity occurs about one hour before high water.

(3) Slack after flood occurs from one to three hours after high water and one or two hours before half tide.

(4) Maximum ebb velocity occurs from one to five hours before low water.

(5) Slack after ebb occurs from one half hour to three hours after low water and from one half to one hour before half tide.

Effect of Run-off.

By subtracting the flood discharge from the ebb and dividing the remainder by the mean area during the period and again by the total time of flood and ebb, an equivalent mean non-tidal or run-off velocity is obtained. The maximum values of this are as follows:—

Pots Tree 1.00 foot per second (North Branch).

Leo Point 1.35 feet (South Branch).

Kiangyin 3.92 feet (entire river).

At Wuhu where tidal effects are very small the mean of all mean velocities observed is 3.66 feet per second and a filament value as high as 6.42 feet per second has been recorded.

It will thus be seen that in the upper river the run-off velocities compare in value with the tidal current velocities in the lower Estuary and that even in the latter they must appreciably enlarge or decrease those velocities.

Erosion Currents.

No current observations have been made at bends or bars where erosion is known to occur but it appears probable that velocities of less than 6 feet per second produce erosion of the alluvial soil of the Yangtse Bed and Banks.

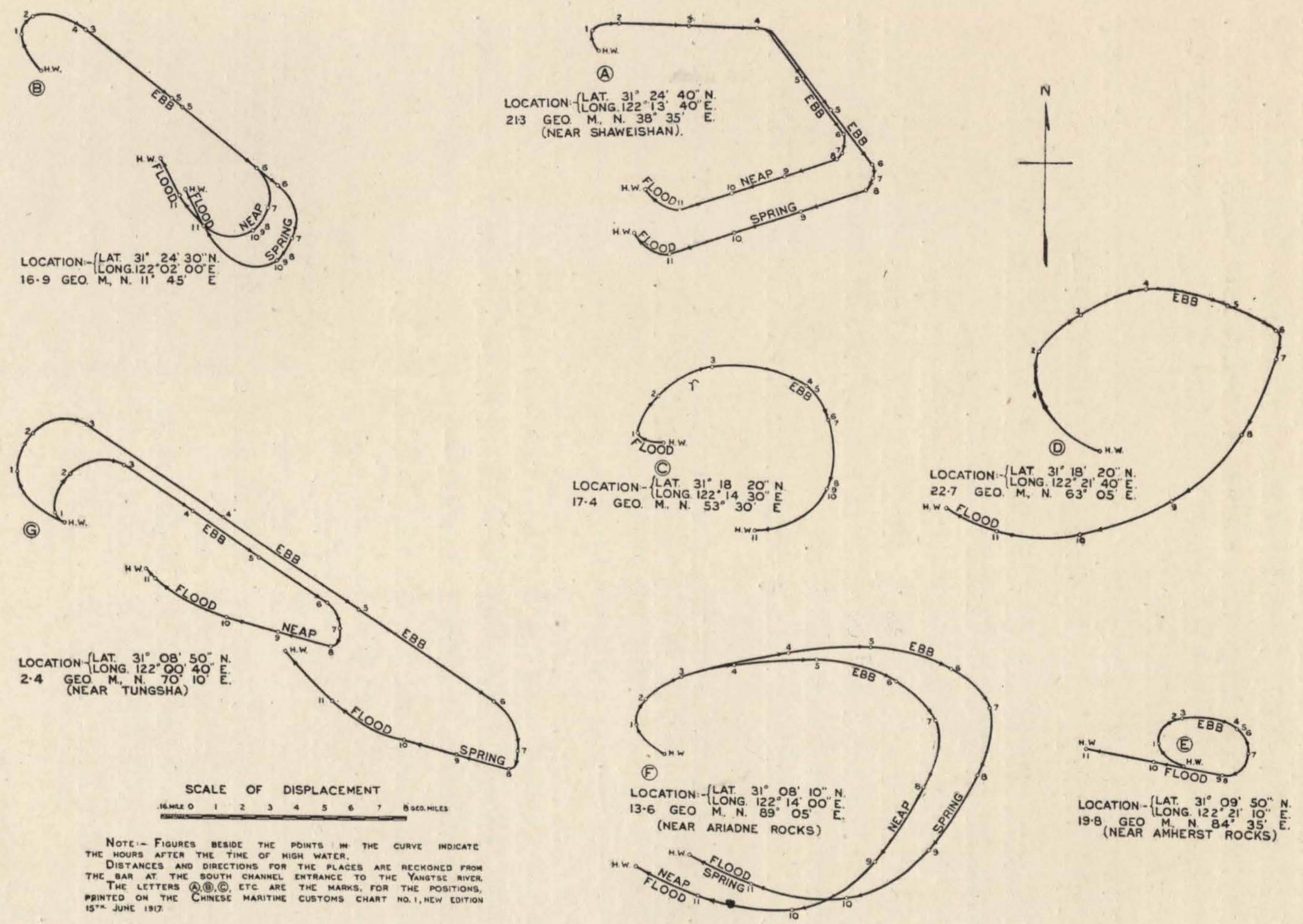
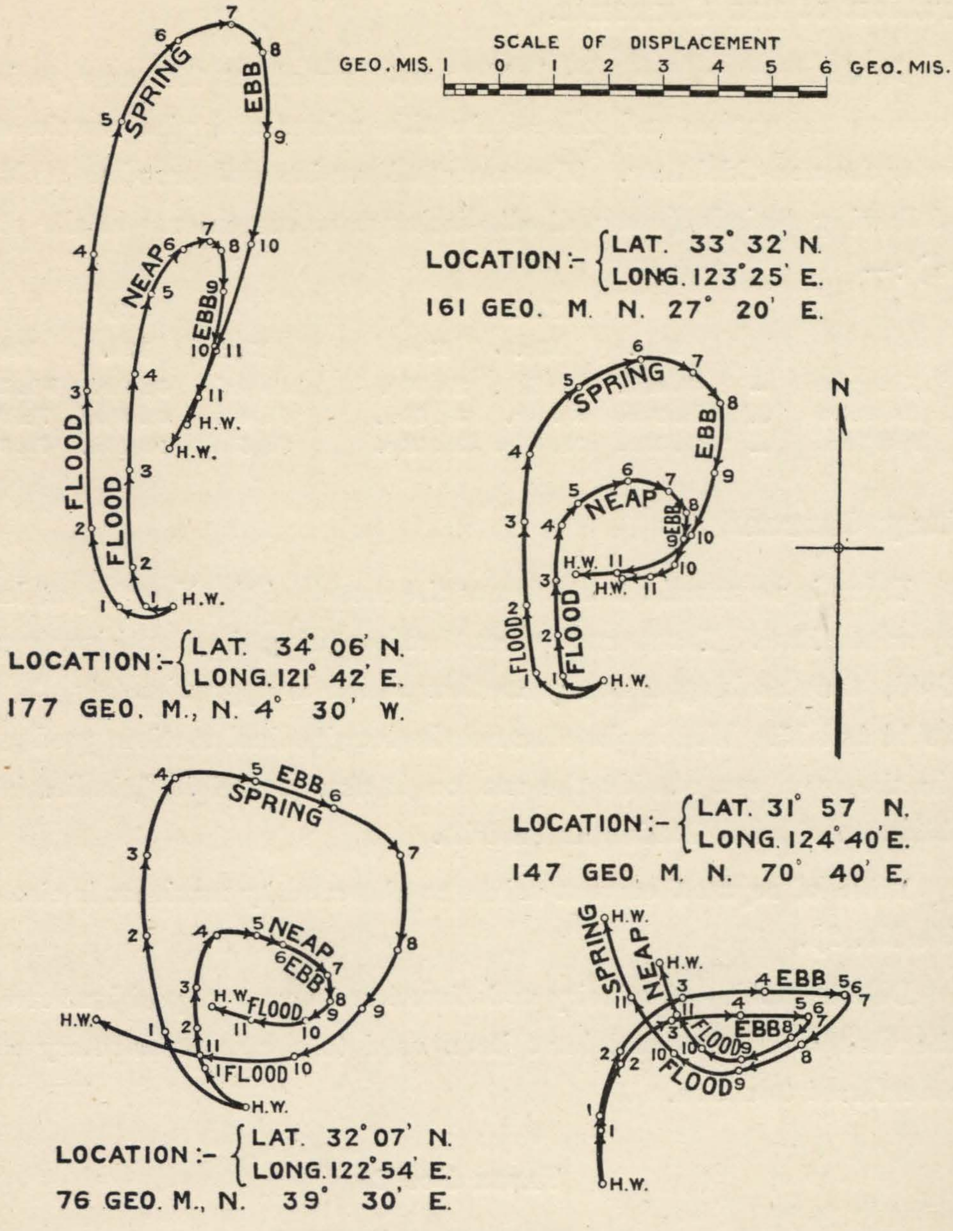


Plate No. 14.—Computed Float Tracks in the neighbourhood of the Mouth of the Yangtse. These are only approximate but probably fairly well represent the actual conditions



NOTE:—FIGURES BESIDE THE POINTS IN THE CURVE INDICATE THE HOURS AFTER THE TIME OF HIGH WATER AT SHAWEISHAN ISLAND—LAT. 31° 26′ N. LONG. 122° 15′ E.; 23 GEO. M., N. 39° 30′ E.

DISTANCES AND DIRECTIONS FOR THE PLACES ARE RECKONED FROM THE BAR AT THE SOUTH CHANNEL ENTRANCE TO THE YANGTSE RIVER.

Plate No. 15.—Computed Float Tracks in the Yellow Sea, showing the Distant Influence of the Yangtse

Duration of the Currents.

In the average, floods and ebbs persist for about the same periods as the corresponding rises and falls of the tide minus and plus certain corrections for the non-tidal flow. The currents have been observed to endure for the following periods (mean of all discharge measurements at the stations given) :—

	Flood			Ebb		
	Max.	Min.	Mean	Max.	Min.	Mean
Kiangyin ...	4h. 42m.	nil	2h. 56m.	whole period	6h. 0m.	10h. 32m.
Leo Point ...	4h. 20m.	3h. 0m.	3h. 52m.	8h. 40m.	6h. 34m.	7h. 36m.
Pots Tree ...	4h. 54m.	1h. 50m.	3h. 53m.	8h. 50m.	4h. 40m.	7h. 56m.

Rotary Currents.

There is no actual slack water at the mouth of the Yangtse, at least as far up as the Bars. Transverse currents exist during the transition from ebb to flood, thus making a rotary motion which is approximately shown in Plates 14 and 15. Within the channel the longitudinal motions predominate but in the open sea outside the motion is almost cycloidal, indicating the combination of an oscillation and a drift.

Table of reputed current values as observed by mariners is also given (Table No. 2).

Detailed tables of velocity and direction for various positions are given on the Customs Charts and have been used to compute the rotary motion curves referred to above.

Table No. 2

TIDAL CURRENTS IN YANGTSE

(Velocities in feet per second: Ebbs positive)

Place	*Interval from Max. Ebb to L. W.*	*Interval from Max. Flood to H. W.*	*High River* Max. Ebb	*High River* Max. Flood	*Lower River* Max. Ebb.	*Lower River* Max. Flood	*Remarks*
Sha Wei Shan	2h. 0m.	3h. 0m.	7.0 (S) 4.2 (N)	−4.2 (S) −3.4 (N)	7.0 (S) 4.2 (N)	−4.2 (S) −3.4 (N)	"China Sea Pilot"
Ariadne Rocks	2h. 30m.	2h. 30m.	5.0	−6.0	5.0	−6.0	
Tungsha Light	2h. 45m.	2h. 0m.	10.0 (S) 5.0 (N)	−5.0 (S) −3.5 (N)	10.0 (S) 5.0 (N)	−5.0 (S) −3.5 (N)	
Woosung	3h. 0m.	1h. 45m.	7.0 (S) 3.5 (N)	−6.0 (S) −3.0 (N)	6.5 (S) 3.25 (N)	−6.25 −3.25	"Yangtse Pilot"

(C) DISCHARGE

Origin.

The flow past any point in the channel arises from two distinct causes which bear a different ratio to one another at different points. These two causes are, of course, run-off and tide. Since the tide is always an important factor below Wuhu all observations of discharge have been taken for tidal periods (i.e., semi-lunar days).

Magnitude.

The total volume discharged past any section in a tidal period ("ebb" or "flood") depends on the amount of run-off which comes through with the ebb, and on the tidal volume which enters (on the flood) or leaves (on the ebb) the "tidal magazine" above the section.

From Table 11 in the Yangtse Estuary Report No. 1, page 52, the following figures for maximum observed tidal discharge for an ebb or a flood period (a fraction of 12½ hours) are found, in millions of cubic feet.

	Flood	*Ebb*
Kiangyin	12,060	173,050 in 24 hours 90,020 in 12½ hours
Pots Tree (North Branch only)	20,260	35,360
Leo Point (South Branch only)	41,620	97,630

The average discharges obtained are shown in Plates 16 and 17.

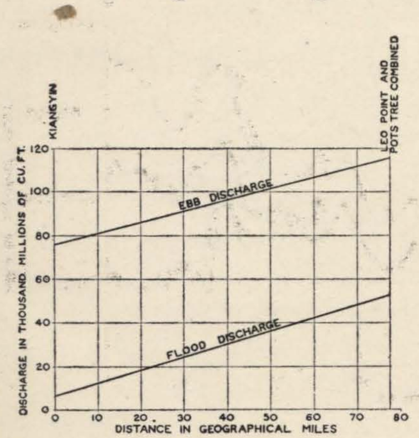


Plate No. 16.—Total Discharges in a Tidal Period, from Kiangyin to Leo Point, during Spring Tides. Based on averages of actual observations

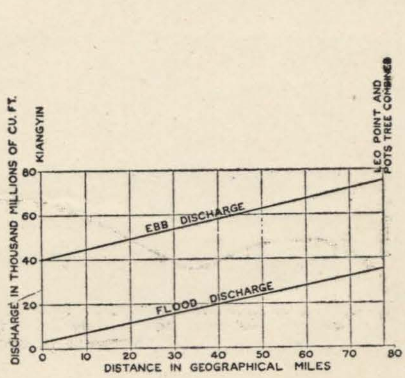


Plate No. 17.—Total Discharges in a Tidal Period, from Kiangyin to Leo Point, during Neap Tides. Based on averages of actual observations

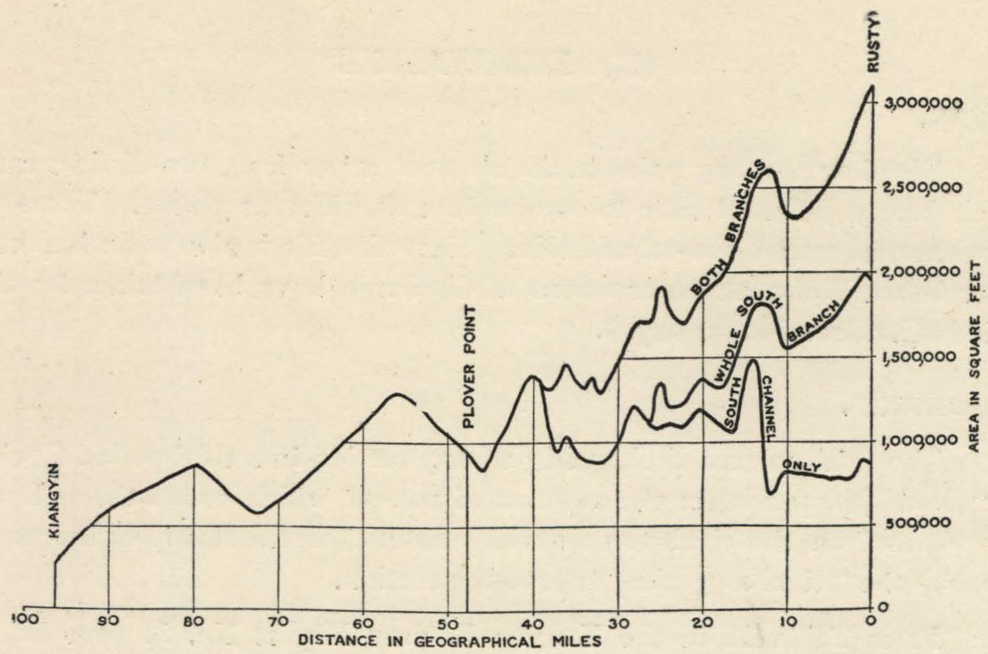


Plate No. 18.—Approximate Sectional Areas below Standard Spring High Water, from Kiangyin to Side Saddle

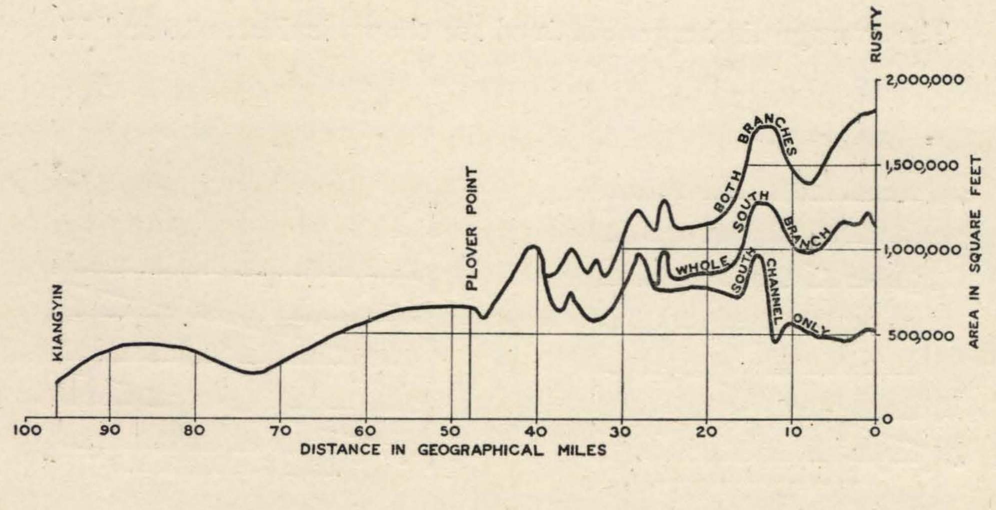


Plate No. 19.—Approximate Sectional Areas below Lowest Low Water from Kiangyin to Side Saddle

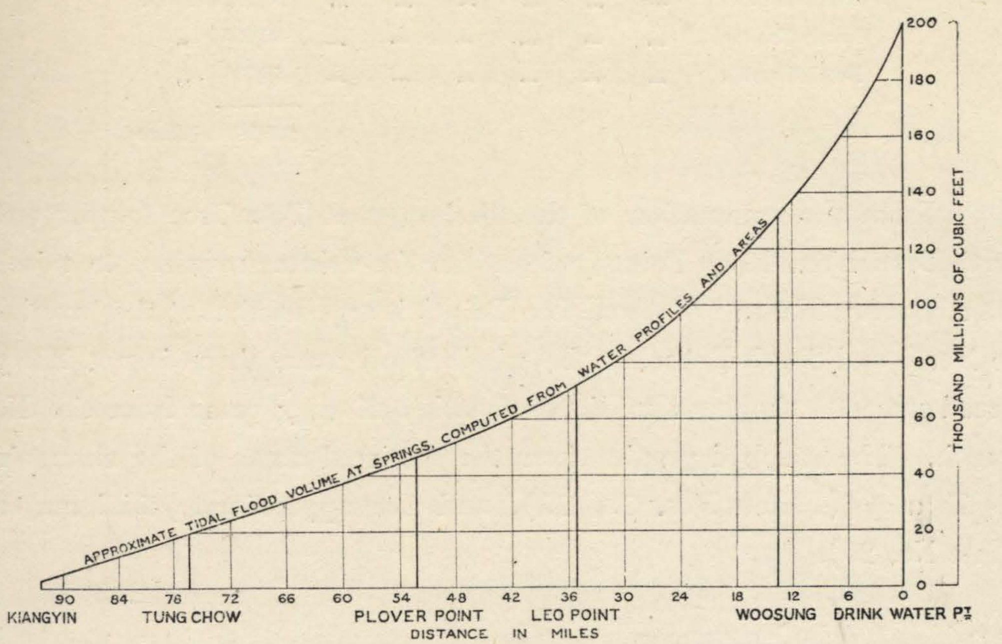


Plate No. 20.—Computed Tidal Volumes passing Various Points from Kiangyin to Drinkwater Point on a Spring Tide Flood

Tidal Volumes.

The volume of water which enters into a tidal river is determined by the range of the tide, the geometrical form of the channel between high and lower lines, the dimensions of the same, the gradient remaining from the previous ebb modified by the run-off, the resistance to the incoming flood, the velocities generated by the given range at the entrance under the peculiar local conditions and the duration of the rise and fall. Hence it is difficult to compute and all rules for doing so are empirical.

According to Stevenson's rule for tidal estuaries,* through the South Channel near Woosung there would be about 45.24 thousand million cubic feet.

For the whole three channels it appears probable from this rule and also our discharge measurements that the influx over the bars has a spring tide value not much less than 250 thousand millions of cubic feet or if the terminal plane be taken at the end of the high-water lines (the "Rusty"—"Drinkwater Point"—"Kiutoan" line) upwards of 200,000 millions.†

This is distributed approximately as follows:—

*Tidal influx=100,000 cu. ft. per sq. ft. of low water sectional area.

†Below this plane the currents on and off the banks complicate matters and are partly in the nature of a coastal "swell."

South Channel	... ...	70,000 millions
North Channel	... ...	80,000 ,,
North Branch	... ...	50,000 ,,
		200,000 millions

From the summation of the discharges at Pots Tree (upper end of North Branch) and Leo Point (reduced for the volume required to raise the water between Mason Point and Leo Point) it appears that at the junction of the North and South Branches the whole flood wave there is not likely to exceed some 60 thousand millions of which 20 may come from the North Branch. The attached graphs show the sectional areas of the channels in the Estuary (Plates Nos. 18, 19), and the approximate tidal magazine (Plate No. 20).

Non-tidal Discharge.

The "non-tidal discharge" or "run-off" is described below (see Sub-section E) but it may be here remarked that it can scarcely ever exceed 3 million cubic feet per second or 135 thousand millions during a tidal period ($12\frac{1}{2}$ hours) and is on a yearly average only about 45 thousand millions. If the mean tidal volume over the Bars is 100,000 millions, the mean non-tidal discharge is about one third the whole ebb discharge over the Bars. The observations made at the head of the North Branch may show that the ebb divides more unequally than the flood so that of the volume corresponding to the run-off less than the fraction corresponding to the areas finds its way out through the North Branch.

Effect on the Yellow Sea.

The non-tidal flow and the reaction from the immense tidal magazine has various effects on the Yellow Sea. It decreases the salinity for many miles, causes a transverse current which combined with an oceanic one produces the rotary motion already alluded to, and it actually raises the surface in the flood season by upwards of a foot as far out as the Saddle Islands.

(D) SILT

Origin.

The Yangtse water is charged with finely divided particles in suspension. From the fact that alluvial soil of a practically constant character occurs right up to Shasze (Shasi), it may be deduced that originally this silt-formed alluvium is produced from the detritus eroded from the mountainous area of the Upper Yangtse. The silt present in the water is either brought down directly from the upper torrents or has been eroded from and replaced by similar material in the alluvial plain. The physical character of the silt is that of a fine loam with a high proportion of sand.

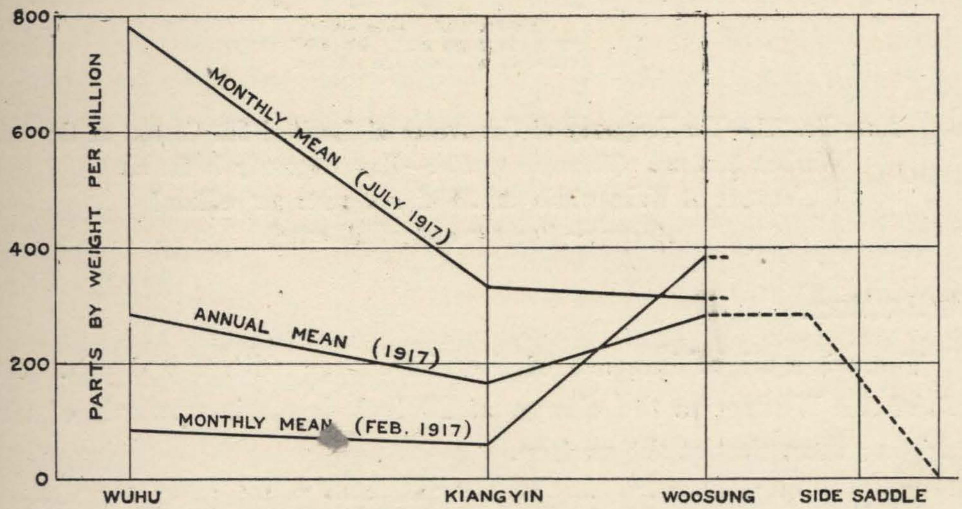


Plate No. 21.—Silt Content of Water at Various Points along the Yangtse, 1917

Magnitude of the Charge.

The observation of silt in the Yangtse has not been continued over a sufficient number of years to show conclusively what the average charge is, but the attached graph (Plate No. 21) shows what the figures were for 1917 (a low year). It will be observed that the silt content per unit volume of water diminishes downstream above the Estuary presumably owing to dilution of the run-off by the tidal volume reducing the silt content at the period of observation (high-water slack) and increases again in the Estuary owing to the disturbance of the bottom by tidal currents. A statistical analysis of all our observations shows that the frequency of the silt ratio at the various points is as shown in Plate 22. The horizontals indicate what percentage of the whole observations lie within 25 parts per million of a specified number.

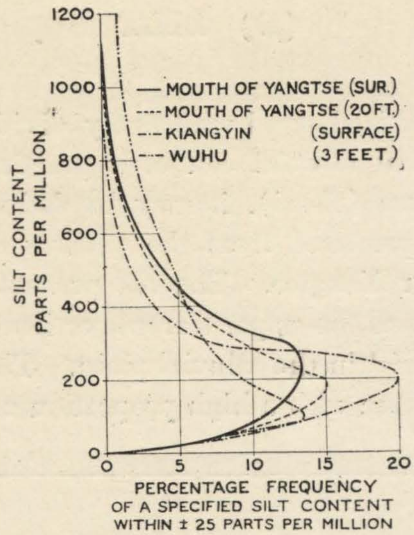


Plate No. 22.—The Frequency of Occurrence of Specified Silt Content at the Various Stations. (*Example of Use:*—**How frequently is the silt content at Wuhu within ± 25 of 600 parts per million?** *Answer:*—**One per cent of all cases)**

Distribution.

There is a slight increase of the silt charge with the depth. At the mouth of the Whangpoo the charge at 20 feet depth is upwards of ten per cent higher than that at the surface.

From a prolonged observation at Pheasant Point in the Whangpoo it appears that the ratio of the silt charge near the bottom to that at the surface is about 1.66 but varies from below unity upwards according to the velocity.

No appreciable variation across a section has yet been recorded.

Longitudinally the silt charge is related in some manner to the velocity but except for the changes noted in the previous paragraph, no data have been obtained.

Precipitation and Silt Equilibrium.

Most of the silt consists of very fine particles which settle very slowly, i.e., less than 1 cm. per second, the diameter being less than one tenth of a millimeter.

The precipitation from unit volume in unit time varies approximately as somewhat more than the square of the silt content.

The individual grains have a specific gravity of about 2.7. The dry powder in bulk has a specific gravity of 1.25 and as wet mud 1.75. The silt content in parts per million by weight in the Whangpoo from samples taken at high-water slack at 20 feet depth is very approximately about 15 v^2 where v is the maximum filament velocity of the preceding current in feet per second.

The maximum rapidity of silting on a horizontal surface in a cul-de-sac at the mouth of the Whangpoo is about 3 feet per annum which appears to be in excess of the silt in suspension, but may be partly due to the creep of a thin layer of bottom mud with the more rapid flood current.

The velocity of equilibrium for a stream in alluvial soil is generally supposed to be that which stirs up the bottom by vertical eddies generated from the rugosities of the bed (the said eddies expanding as they rise and descending with a much reduced vortical spin) to an extent which imparts just as much silt to the water as is precipitated by gravity in the same time. According to Indian canal experience this velocity varies as the two-thirds power of the depth. This is partly supported by Yangtse, Whangpoo, and creek experience.

The speed of precipitation is modified by bacterial culture, by addition of alum or dilute acids, and by admixture with salt water.

Variations.

In the Estuary there are the following periodic changes in the silt charge:—

(1) *Six-hour period:*—This is due to the periodic tidal current velocity. The fine silt settles very slowly (according to experiments the rate of precipitation varies as about the cube of the silt content) and the majority of the silt descends less than 1 cm. per second, so that during the period of falling velocity the actual change in silt content is small unless the previous maximum velocity has been high and has produced a rich charge. The large number of analyses required has prevented obtaining any very exact relation of silt content to hourly tidal phase for the Yangtse but it appears certain that during neap tides the silt content is almost constant (i.e., the charge being small the rate of precipitation is very small and there is no appreciable loss during the time when the velocity is less than that corresponding to the silt content).

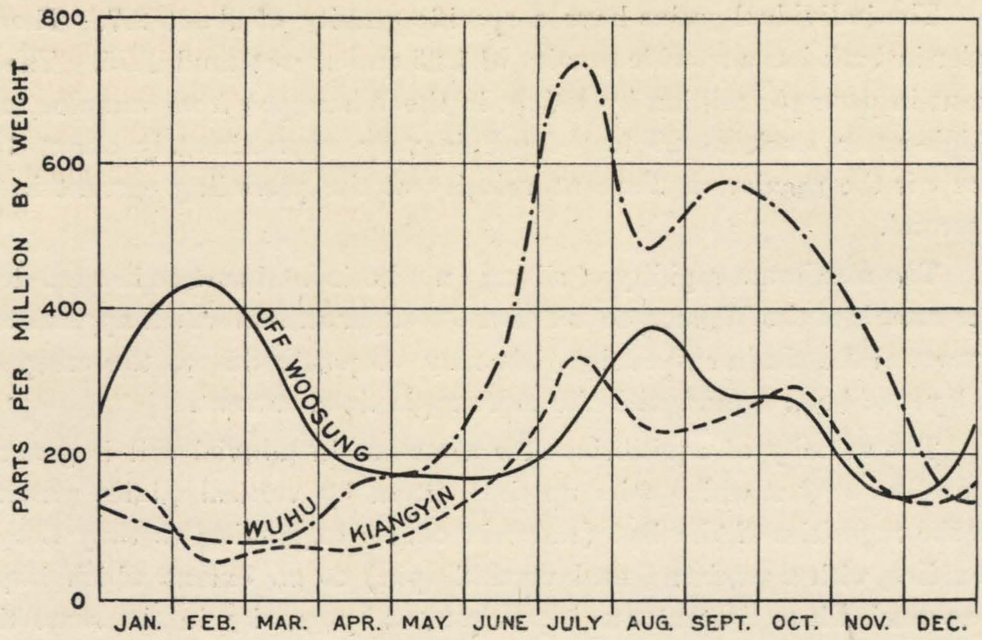


Plate No. 23.—Variation of Silt Content during the year at Various Stations

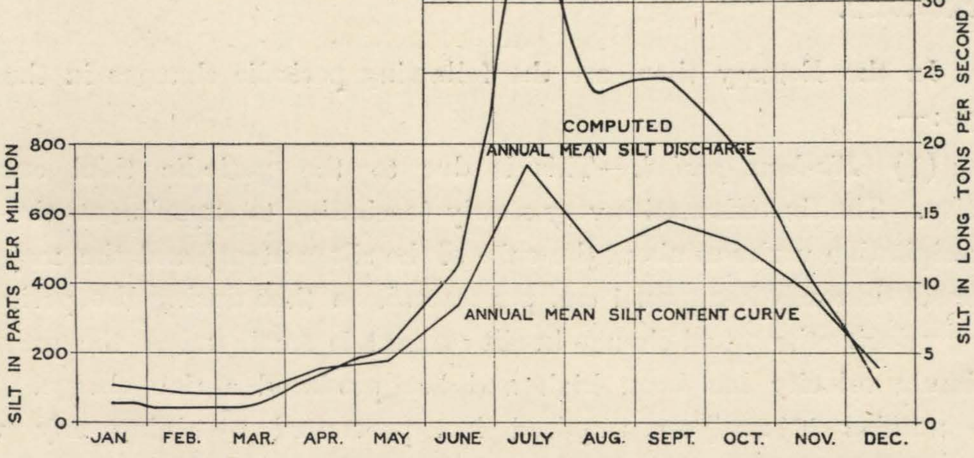


Plate No. 24.—Variation of Silt Discharged past Wuhu during the year, computed from the Silt Content and Run-off

(2) *Fortnightly period:*—The succession of strong currents which occurs with spring tides raise the silt content considerably and it appears that the ratio of the silt content on the 2d, 3d, 4th, 16th, 17th, and 18th days of the moon to that on the 9th, 10th, 11th, 23d, 24th, and 25th is about 4. If the three maximum and minimum daily records per half-moon are compared, the ratio is upwards of 6. This difference is undoubtedly due to the following causes:

(a) Maximum and minimum tidal currents do not always occur in true tidal phase.

(b) The period of quadratures does not lie exactly midway between syzygies.

(c) Diurnal inequality may cause acceleration or retardation, so shifting maximum and minimum velocities away from springs and neaps, and

(d) Resultant velocities due to combined currents at any particular point may vary according to the speed of propagation of the competent currents.

(3) *Semi-annual period:*—An unexpected result is that in the lower parts of the Estuary there are two annual maxima and minima (see Plate No. 23) as follows:

February maximum about twice mean value.

June minimum about two-thirds mean value.

August maximum about one and a half mean value.

November minimum about half mean value.

The first maximum appears to be due to the scour which occurs at very low river. The first minimum is a probable result of the dilution caused by early rains and high tides. The second maximum is due to the high stage of the river with strong currents bringing down Szechuan and other silt. The second minimum is the result of the general decrease of the upstream silt supply.

Total Discharge.

Volume of silt:—The annual volume of silt brought down past Wuhu is, according to Yangtse Estuary Report No. 1 (page 65), 11,000 million cubic feet, corresponding to an average of 16½ tons per second. A new estimate based on the 1917 analysis and long period mean levels (see Plate 24) gives an average of about 15 tons per second which at 20 cubic feet per ton comes to almost 10,000 million cubic feet per annum. It should be clearly

understood that the above figures only apply to the freely suspended silt, and that the amounts of silt moving along the bottom have not been taken into account.

Relation of Silt to Mud Volume.

As the silt has a specific gravity of 2.7 the ratio by weight must be divided by this figure to obtain the ratio by volume. In the form of mud (specific gravity 1.75) about 40 per cent by volume is silt, the remainder being water.

Density of Water.

The density of the Yangtse water reduced to 4° Cent. decreases from 1.0002 to 1.0010 at Wuhu to about 1.0001 at Kiangyin on account of the decrease of silt as observed at high-water slack, 3 feet from surface, and rises again to 1.0003 or so in the Estuary. Beyond the Bar the density rises rapidly owing to the salinity and during flood tides as much as 1.025 has been observed at Fairway Bell Buoy. This is the value in the open sea beyond the Saddle Islands. The "Challenger" expedition found that the density rose to a maximum of 1.026 near Japan and decreased toward the China Coast. This decrease is undoubtedly due to the freshwater entering.

(E) RUN-OFF

Origin.

The nontidal discharge in the Yangtse originates in the precipitation on the watershed, but a computed value has but little significance owing to the lack of meteorological observations in the mountainous regions where the precipitation principally occurs.

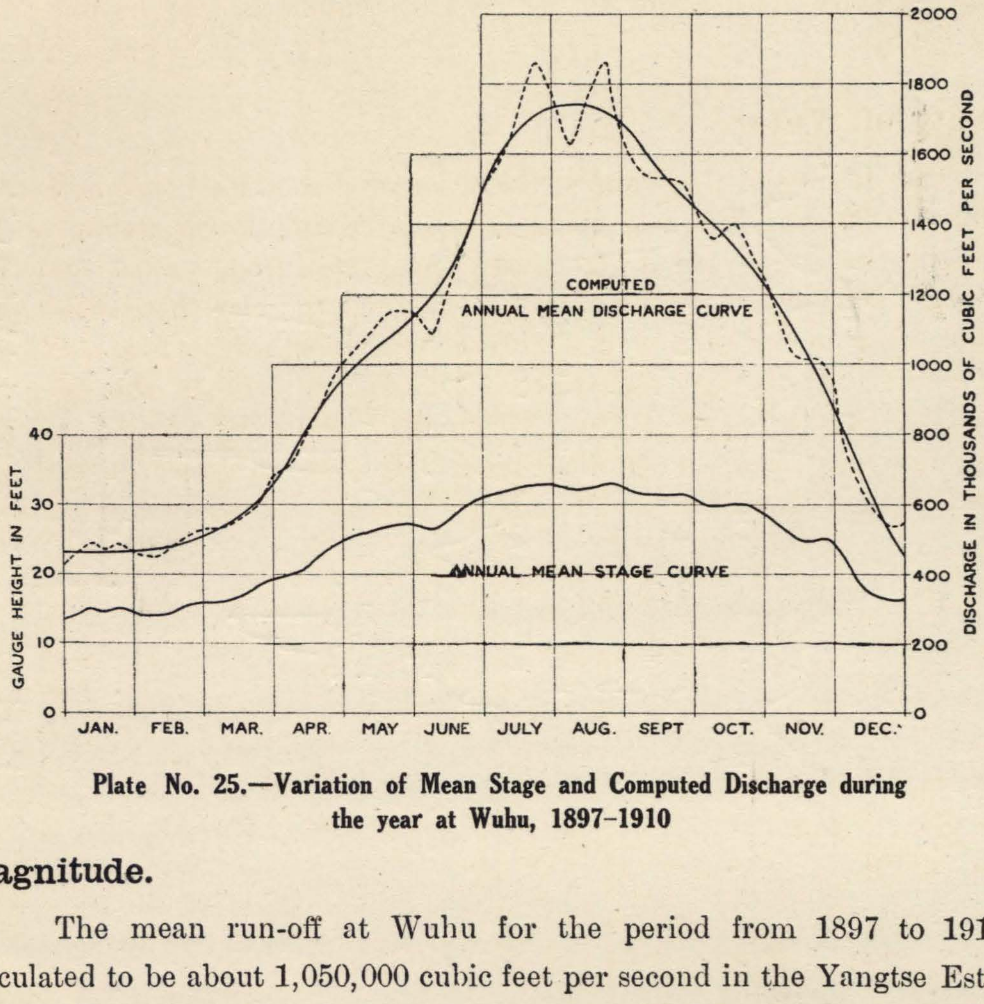


Plate No. 25.—Variation of Mean Stage and Computed Discharge during the year at Wuhu, 1897–1910

Magnitude.

The mean run-off at Wuhu for the period from 1897 to 1910 is calculated to be about 1,050,000 cubic feet per second in the Yangtse Estuary Report No. 1, page 57. The graph, Plate 25, which has been compiled from the mean stage curve during the year (being the average of all the years 1897–1910) and the rating curve (Plate 58, Yangtse Estuary Report No. 1, in Folder) shows how the run-off changes through the year. The maximum is about 3,000,000 cubic feet per second and the minimum 250,000 cubic feet per second.

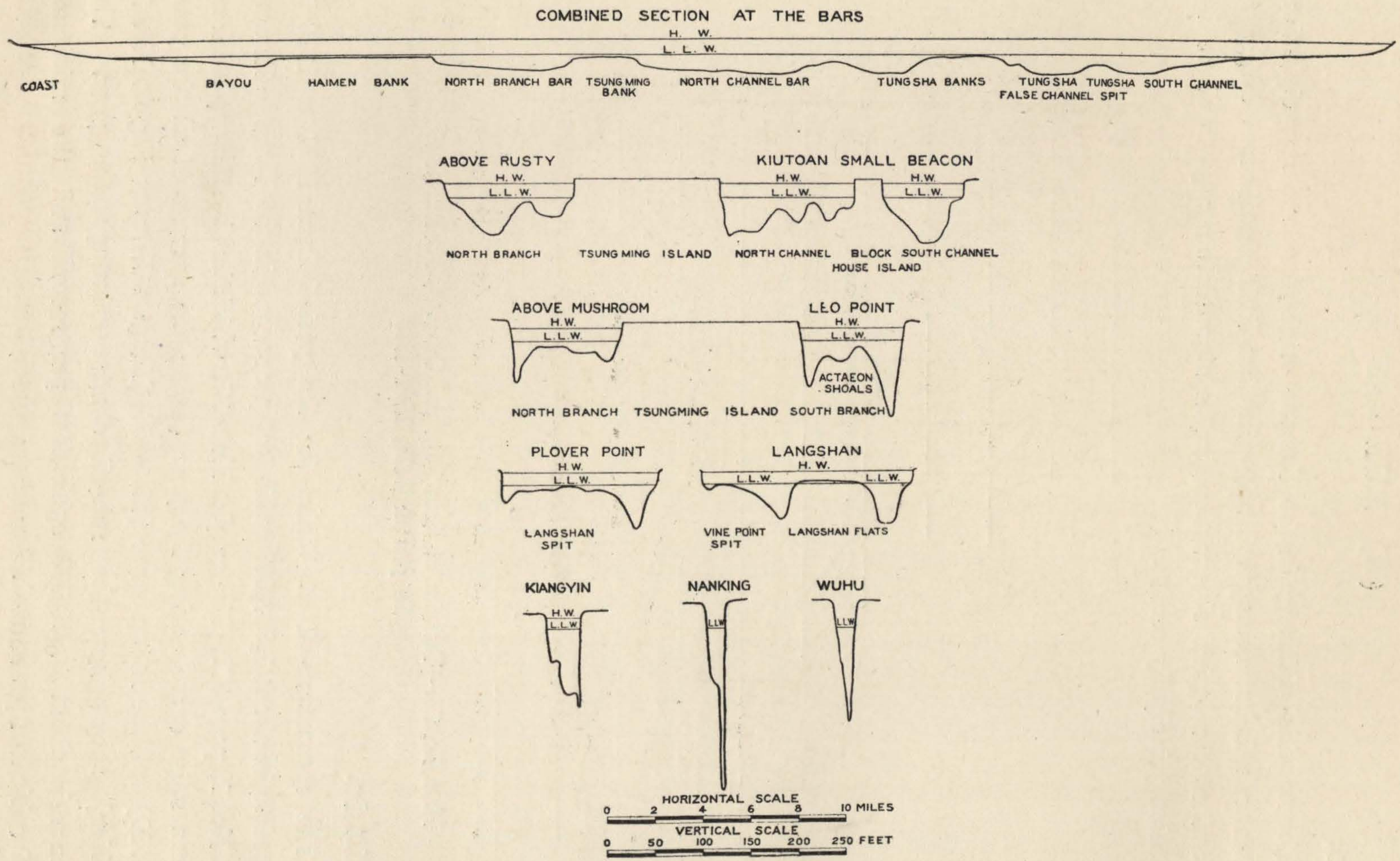


Plate No. 26.—Sections of Yangtse at Various Points

Note:—**The section at the Bars follows a curved line in plan**

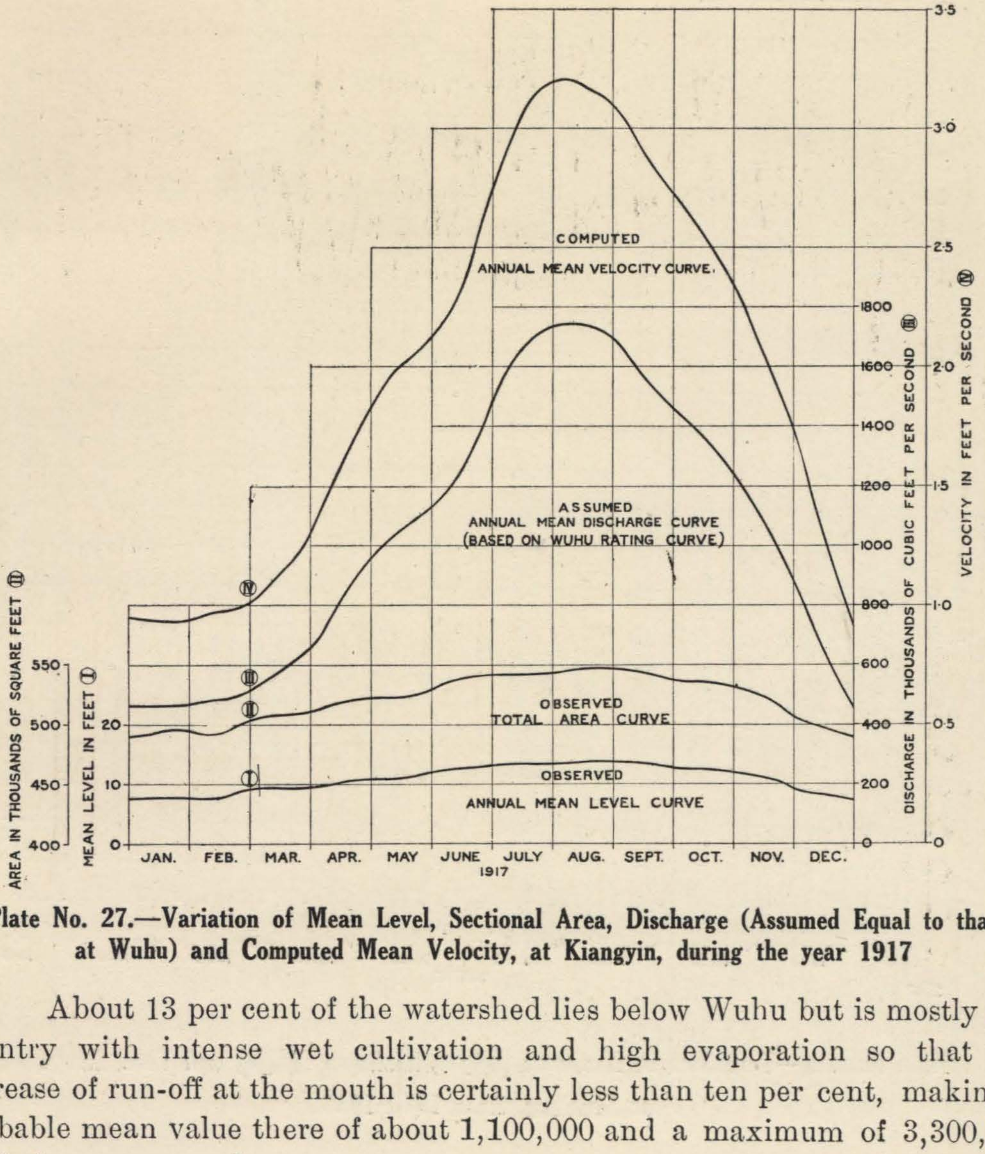


Plate No. 27.—Variation of Mean Level, Sectional Area, Discharge (Assumed Equal to that at Wuhu) and Computed Mean Velocity, at Kiangyin, during the year 1917

About 13 per cent of the watershed lies below Wuhu but is mostly low country with intense wet cultivation and high evaporation so that the increase of run-off at the mouth is certainly less than ten per cent, making a probable mean value there of about 1,100,000 and a maximum of 3,300,000 cubic feet per second.

Run-off Velocities.

The cross-sectional areas of the Estuary are shown in Plate No. 26. The maximum and mean velocity for the whole section corresponding to the resistance of the soil is between 3 and 5 feet per second.

At Plover Point the area at mean tide level is about 600,000 square feet, so that the imaginary equivalent mean "run-off" velocity (i.e., the average resultant rate of the freshwater proceeding toward the sea) is from 0.4 to 5.0 feet per second. At the Bars (outer end of Tsungming Island) the

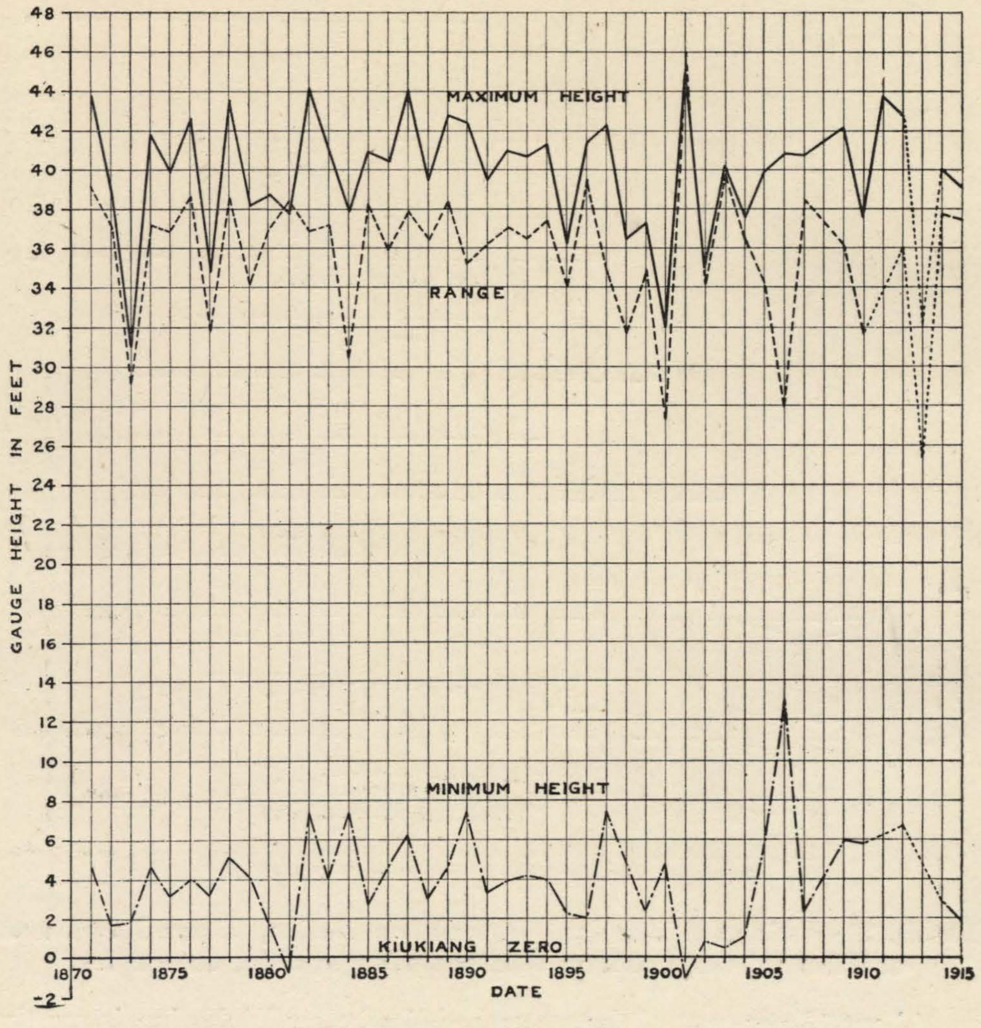


Plate No. 28.—Variations in Maximum Height, Minimum Height, and Total Range, at Kiukiang, from 1870–1915

total area of the water section is something like 3,000,000 square feet, so that the equivalent run-off velocity there is from 0.1 to 1.0 foot per second.

Diagram of run-off velocities at Kiangyin for one year computed from Wuhu discharges are shown in Plate 27.

It will thus be seen that the ratio of the equivalent run-off velocity to the tidal current velocities (which amount to from 5 to 7 feet per second at Plover Point) is from, say, 0.06 to almost unity at Plover and with a

maximum velocity of, say, 8 feet per second at the Bar, the ratio is from 0.01 to 0.13. These figures will be almost doubled in the lower parts of the Estuary if it is considered that run-off only occurs during ebbs.

It thus appears that the "run-off" velocity is an important factor in the *maximum* strength of the current, say above Woosung, but only causes slight differences in the current below that place.

Variation from Year to Year.

The graph (Plate 27) shows the maximum and minimum stage at Kiukiang from 1871 to 1910 which fluctuates about 50 per cent more than Wuhu but has the advantage of being entirely free of tidal influence. 1901 and 1911 are the two highest years.

(F) SLOPE

General Configuration of the Yangtse Valley.

Above Ichang the slopes are large and the flow is torrential but below that place the fall is very moderate so that spate and (in the Estuary) tide conditions produce great relative changes.

Mean Profile.

Plate No. 29 shows the mean-water profile from Wuhu to Side Saddle and also the Highest High-Water and Lowest Low-Water Lines.

All these lines are imaginary since the tidal waves are always in existence but they doubtless approximately correspond to the run-off. A set of instantaneous water profiles is shown in Plate No. 27.

Magnitudes.

The maximum observed flood slope is 0.00008 near Plover Point, but there is almost a "bore" effect with infinite flood slope at certain times over some of the shoals. The maximum ebb slope observed is 0.00004 in the same locality.

Relation Between Slope and Velocity.

Attempts have been made at Wuhu to correlate the velocity to the slope and hydraulic radius on the lines of the different standard velocity formulæ but the difficulties, observational and mathematical, are very serious. There is doubtless an acceleration correction (Whangpoo Report No. 2, pages 67–77) and it also seems certain that "dissipation"—i.e., irrecoverable loss of energy due to eddying at changes of section and changes of direction plays a large part when a considerable length of the stream is considered.*

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*The following formula fairly well expresses the conditions in a reach with equal end water sections

$$v = C_0(1-k)R^{0.7}\left(I - \frac{a}{g}\right)^{0.5}$$

When C_0 is the coefficient for an artificial regular uniform channel.

k is the dissipation factor for a natural channel.

R is hydraulic radius.

I is slope, a is dv/dt, v = mean velocity, g = gravitational acc.

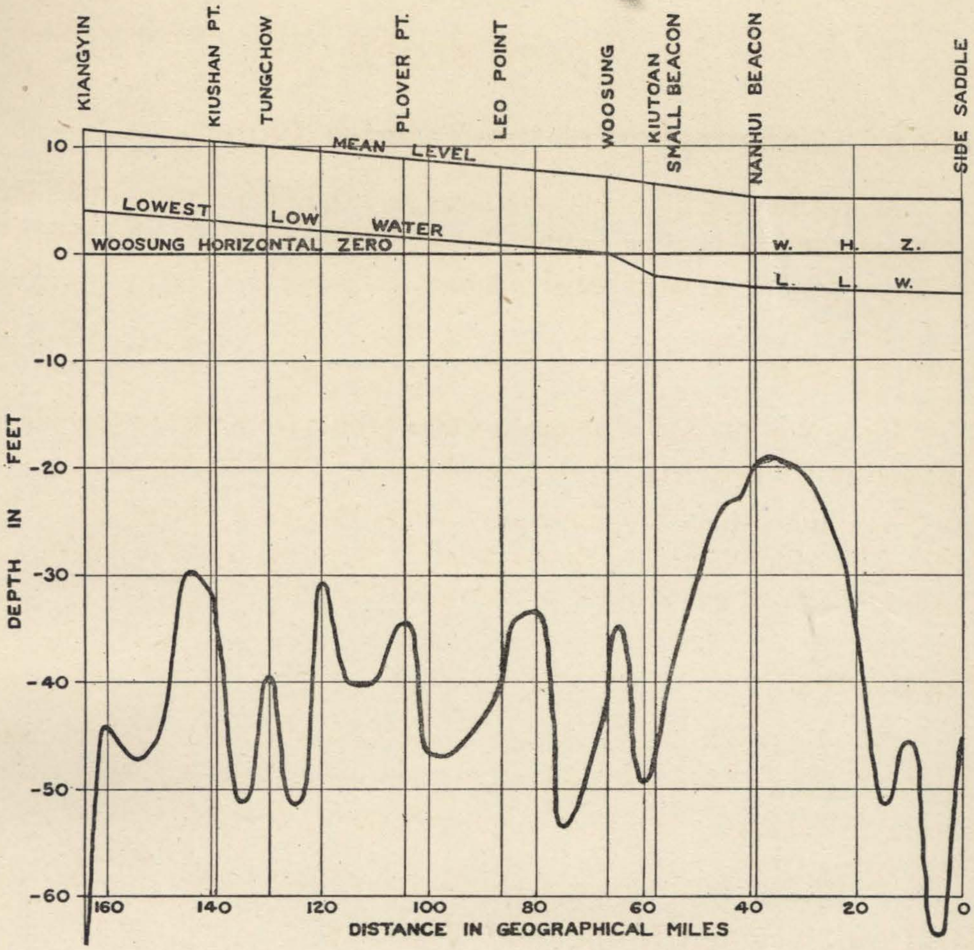

Plate No. 29.—Mean Level, Lowest Low Water and Profile of Bottom of Channel from Kiangyin to Side Saddle

The "Stage" of the River.

The "stage" at Wuhu is of course a rough indication of the slope from there to the sea, and the discharge is related to it in a complex manner which is described in the first Yangtse Report. Its relation to the local slope cannot be determined without comparison with the stages at other points above and below and the accurate levelling of the necessary tidepoles to a degree commensurate with that of the minute differences of level to be observed.

Shanghai, May, 1919.

H. von HEIDENSTAM,
Engineer-in-Chief.